Laser Communication Demonstration System (LCDS) and Future Mobile Satellite Services

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ABSTRACT

The Laser Communications Demonstration System (LCDS) is a proposed in-orbit demonstration of high data rate laser communications technology conceived jointly by NASA and U. S. industry. The program objectives are to stimulate industry development and to demonstrate the readiness of high data rate optical communications in Earth orbit, For future global satellite communication systems using ISLs, laser communications technology can offer reduced mass and power requirements and higher channel bandwidths without regulatory constraints. As currently envisioned, LCDS will consist of one or two orbiting laser communications terminals capable of demonstrating high data rate (greater than 750Mbps) transmission in a dynamic space environment. Two study teams led by Motorola and Ball Aerospace are currently in the process of conducting a Phase A/B mission definition study of LCDS under contracts with JPL/NASA. The studies consist of future application survey, concept and requirements definition, and a point design of the laser communications flight demonstration. It is planned that a single demonstration system will be developed based on the study results. The Phase A/B study is expected to be completed by the coming June, and the current results of the study are presented in this paper.

INTRODUCTION

The market for satellite services world-wide is expected to grow significantly in the next decade. This growth is fueled partly by the emergence of global mobile satellite services. These mobile services combine the advantages of universal coverage and wide bandwidth with reliable services for the increasingly mobile world. This potential of providing global interconnect will enable companies to cost-effectively transmit data (fax, email, voice, and other electronic data interchange) around the world, including under-developed nations and rural areas. Furthermore, these services permit users to access satellite transponders on demand and hence can significantly reduce the cost to end users for satellite services. The mobile satellite industry is expected to be a multi-billion dollar industry in the coming years (possibly $6.5 billion by the end of 1995 and to $17 billion by 20031). Shown in Table 1 is a partial list of global mobile satellite services currently under development. The growth of global mobile services has led to an increasing demand on bandwidth and frequency allocation. Furthermore, it has led to a renewed interest in high data rate intersatellite links as a method of routing information between satellites,

A high data rate intersatellite link (ISL) is an important technology for future global mobile satellite services. ISLS experience neither transmission fades nor multipath, and can maintain effective link margin with a lower power requirement than ground-based routing. The use of intersatellite links can permit global data distribution without multiple hops through ground stations. Additionally, with the short propagation delay to a LEO orbit, it is envisioned that a LEO satellite network using lasercom technology can be part of a global information network that provides seamless interconnect capability with terrestrial fiber optic networks. This application would provide complete transparency for delay-sensitive ground-based computer communications protocols. ISLs can also be applicable in long-haul services to eliminate double-hop connections between destination points. Another possible application for ISL is to connect cluster satellites to enhance capacity, and to permit the use of smaller, modular, low cost, and low risk satellite designs.

Two of the most ambitious Mobile systems (Iridium™ and Teledesic™) will rely on ISLS to provide global coverage. The Iridium constellation has 66 satellites in 6 orbital planes, with 4 crosslinks on each satellite (front, back, and two in adjacent orbits). The Teledesic constellation has 21 orbital planes with 40 satellites each for a total of 840 LEO satellites and 8 crosslink connections from each satellite. Each satellite in the constellation will communicate and route network traffic to provide direct and practical routing between users throughout the world, and provide a substantial redundancy that can continue to support traffic flow in the event of degradation to one of the satellites. Because of the. large number of satellites and consequently the number of crosslink terminals (264 for Iridium and 6720 for Teledesic), minimizing the mass and power of the

Name	Altitude/# orbital planes	Total # satellites	Mass per satellite	Intersatellite Links	Services Offered	System Cost
MSAT	GEO/1	2	2500	No	voice, data, fax	$500 million
Globalstar	14ookm/8	48	250	h'o	voice, data, FAX, paging, RDSS	$1.8 billion
Iridium	780/6	66	700	Ycs	voice, data, Fax, paging, RDSS	$3.4 billion
Odyssey	10400km/3	12	1900	No	voi ce, data, Fax, paging, RDSS	$1.3 billion
Project-21	10355/2	10	1960	Maybe	voice, data, fax, paging, navigation	$1-2 billion
Teledesic	700/21	840	750	Yes	broadband services	$9 billion

Table 1. Mobile satellite services currently under consideration.

crosslink terminal is mandatory for these systems. For example, the baseline Teledesic satellite has allocated only 144 kg for its communications payload[2]. This includes 8 crosslink terminals and the main mission antenna. Similarly, the Iridium system has baselined 165.1 kg for its communications payload[3], including the four crosslink terminals and four gateway moveable antennas. The large number of crosslinks per satellite can also impose constraints on the size of the antenna as it affects the spacecraft packaging and the size of the launch fairing.

Lasercom technology, with its mass, power, and size advantages, can provide a viable solution to these needs. Additionally, laser-based ISLs are not susceptible to radio-frequency interference (RF]), and no frequency allocation or bandwidth constraints exist for the optical frequencies. Furthermore, because the laser terminals can transmit and receive on the same wavelength, all satellites in the constellation can be made identical. This interchangeabil it y of lasercom terminals and Satellites is another factor that will minimize the cost for these commercial ventures (an advantage that can not be provided by RF).

Despite the relative advantages offered by the lasercom technology for intersatellite applications, potential users have been slow to embrace the technology. This is in part because past development efforts were conducted before the technology is ready. More importantly, there have been concerns about the perceived difficulties in establishing an optical link between moving platforms. To address these concerns and to gain user acceptance of the technology, a functioning demonstration under a relevant operating environment has been regarded as a critical step. A successful demonstration can address the user concern by validating mutual acquisition and accurate beam pointing from space platforms with vibrational spectra representative of future user spacecraft. A space-based demonsfration can also validate the design, performance, and operating lifetime of the terminal under high vacuum, radiation, and space debris environments similar to the expected user conditions and in the presence of bright sunlight.

LCDS PROGRAM OVERVIEW

The Laser Communications Demonstration System (LCDS) is a joint NASA-U.S. Industry program to demonstrate high data rate lasercom technology under a dynamic orbital environment. The objectives of the LCDS program are to:

(a) Identify the user base and potential applications for lasercom technology,

(b) Demonstrate lasercom technology in a relevant operating environment envisioned for future users. This demonstration should be derived from and traceable to future applications. Furthermore, it is essential that the demonstration be successful and timely.

(c) Facilitate development of industry base for lasercom technology

LCDS will consist of one or two orbiting laser communications terminals capable of demonstrating high data rate (greater than 750 Mbps) transmission in a dynamic space environment. Two industry teams, one led by Motorola Inc. with participation by Martin Marietta Technologies Inc., and the other led by Ball Corp. with participation from Thermotrex, Comsat Laboratory, Astrotcrra, Laser Diode Systems Corp., and Daedalian Technologies, have been selected for the Phase A/B Mission Definition study to define an in-orbit demonstration of lasercom technology with a goal of demonstrating at least 750 Mbps data rate.

The Phase A/B Mission Definition study includes the following task areas:

Application	LEO-GEO	LEOLEO	LEO-Ground
32GHz	46 cm LEO aperture, 75lbs, 95W 4.9 m GEO aperture, 1 10 lbs, 55W	38 cm aperture, 8 0 lbs, 80 W	46 cm aperture, 65 lbs, 45 W 5 m ground aperture
60 GHz	46 cm LEO aperture, 75lbs, 80W 4.9 m GEO aperture, 110lbs, 60W	38 cm aperture, 80 lbs, 75 W	N/A
Optical	18 cm LEO aperture, 55 lbs, 90W 30 cm GEO aperture, 60 lbs, 75W	16.5 cm aperture, 22 lbs, 25 W	16.5 cm aperture, 22 lbs, 25 W 1 m ground aperture

(a) Application Survey: Identify future commercial and government space applications to identify areas where lasercom is applicable, cost effective, and competitive.

(b) Demonstration Design: This includes the development of the demonstration objectives and concept based on the assessment of future markets, definition of the demonstration system and subsystem requirements, point design of the demonstration, and assessment of the technologies required for the demonstration. Also included in this task are the definition of the mission operations concept, and assessments of the launch vehicle and host spacecraft.

(c) Development of a life cycle cost estimate and Phase C/D program development plan.

The Phase A/B studies is expected to be completed by the coming June, and JPL is in the process of preparing a consolidated program plan for submission to NASA.

COMPARISON OF RF AND LASERCOM SOLUTIONS TO 1S1.

The application surveys conducted under LCDS indicated, as expected, that most future applications for lasercom will be for high data rate intersatellite links, with a majority of the links operating at medium (2000 - 6000km) range, although a few demanding applications will require cross] inks over the geosynchronous arc (e.g. TDRSS follow-on, etc.). Based on the application survey, a comparison of RF and Lasercom ISLS was Conducted.

The technical merit of laser ISLS is derived principally from the highly collimated optical signal, and hence a greatly increased transmit power efficiency compared to conventional microwave systems. The improved power efficiency can lead to a terminal design with greatly reduced size, mass and power requirements. By virtue of shorter wavelength and higher operating frequency, a lasercom system also offers wider information bandwidth. Furthermore, lasercom systems are not susceptible to radio frequency interference and are not subject to frequency or bandwidth regulation. The combination of these advantages makes lasercom highly attractive for ISL applications.

Comparisons of ISL implementations using optical and RF technologies were conducted under the LCDS activity for both LEO-LEO and LEO-GEO crosslinks. RF technologies for 30, 60, and 90 GHz ISLS were assessed and projected for a 1999 deployment date. Shown in Table 2 is a summary of RF system performance and comparable lasercom system designs for a 750 Mbps link. 90 GHz ISLS were not included because of its relatively immature technology status for the 1999 time frame.. For the LEO-GEO link, the RF LEO terminal is assumed to have a modest antenna size (0.45 m) with a 55% antenna efficiency and a transmit power of 25W with 1.5 dB circuit loss. The GEO terminal has a 4.88m aperture mesh antenna and an uncooled MMIC InP HEMT front end with a noise figure of 1.5d B. The expected antenna noise temperature of 230K results in an overall system noise temperature of 350K. In addition, there is an assumed 1.0 dB receiver circuit loss, and a 5.6 dB coding gain, For the LEO-LEO link with a deep space background, the antenna temperature is assumed to be 10K, resulting in a system noise temperature of 130K. The antenna diameter is scaled to 38 cm to provide a 3 dB link margin,

It is seen in Table 2 that a lasercom ISL requires substantially less mass and power compared to the RF solutions for the LEO-LEO and LEO-ground links. Furthermore, lasercom technology offers large growth potential as the data rate can be improved easily by increasing the transmit power or reducing the beam divergence.

In addition to size, mass, and power, lasercom ISLs can also have potential cost advantages over RF links. Because of the high complexity of the laser ISL, it has previously been thought that only the most demanding users such as the military can "afford" lasercom systems. However, the recent emergence of large constellation

Demonstration	Topics
Acquisition and Tracking	• Initial Acquisition • Track and Communicate • Reacquisition
Data Communications	• Random and burst errors • Near sun performance
Life and Operational Reliability	• Design reliability • Laser lifetime • Laser wavelength drift • Orbital Environment issues, including thermal loading, optical contamination, space debris, high vacuum, and radiation,

Table 3. Performances to be demonstrated in-orbit by LCDS.

LEO mobile satellite systems such as Iridium™ and Teledesic™ have redefined the potential markets for intersatellite links. Each of these constellations will require a large number of crosslinks to channel data and status information between satellites. With the large number of terminals, design to unit production cost (DTUPC) processes will be adopted to lower the cost of the lasercom terminal. Cost assessments conducted under the LCDS study indicated that lasercom is not only competitive in the demanding LEO-GEO or GEO-GEO links, but also for the high volume LEO-LEO links.

In addition to intersatellite links, lasercom technology can also be applicable for space-to-ground data return. The rapidly expanding commercial market for high-resolution remote sensing will require large amounts of image data to be transmitted from sensor satellites to data processing and distribution sites, or directly to end users. A space-to-ground link can also be part of an integrated global network that provides high rate data distribution and seamless interconnect with the terrestrial fiber optics networks. However, until the development of a ground infrastructure to support weather diversity reception, space to ground links will be limited to non-real-time data transmission and relay as the availability of an optical link through inclement weather is severely limited.

DEMONSTRATION OBJECTIVES

Based on the characteristics (range, data rate, background condition, etc.) of the identified applications, the LCDS demonstration concepts were developed to support an on-orbit experiment to demonstrate and validate all aspects of a 750 Mbps link. Specific technical objectives of the demonstration include

Demonstrate link performance in a relevant environment:

The primary objective of LCDS is to demonstrate lasercom technology in an operating environment similar to that of the projected applications. The demonstration must also address any user concerns regarding the readiness of the technology. The link performance characteristics to be demonstrated are summarized in Table 3, and include the following

Acquisition and Tracking: Spatial acquisition and fine tracking of a narrow optical signal has long been regarded as the most difficult aspect of lasercom system implementation. This is because, even though a lasercom system derives most of its performance advantages by virtue of a narrow transmit beamwidth, the narrow beamwidth also imposes stringent demands on signal acquisition and beam pointing. To acquire such beams, a beacon signal from the intended receiver must be acquired and tracked by the transmitting terminal. This problem is complicated by the fact that the platform onto which the lasercom system is mounted will experience random vibrations due to on-board mechanical noise. The magnitude of the noise is typically larger than the transmit beamwidth. Furthermore, in order to compensate for the relative motion of the spacecraft, the transmit signal needs to be pointed ahead of the apparent position of the receiver. This point-ahead angle is also typically comparable to, or larger than the transmit beamwidth. Demonstration of the acquisition, tracking, and subsequent beam pointing functions must be conducted under realistic range., power, and platform vibration conditions. Effective demonstration of the spatial acquisition and tracking is a critical step in gaining user confidence in the technology.

Data **Communications:** Efficient modulation and reception of data in the presence of optical background conditions similar to future applications need to be validated in a space environment. Effective handling of the burst errors introduced by the platform jitter environment also needs to be demonstrated. Additional issues include demonstration of effective transmit-receive isolation and data handling/protocol related to routing of a 750 Mbps data stream.

Life and Operational Reliability: This includes the demonstration of effective designs to provide suitable lifetime and reliability of the communications terminal. Issues to be considered include the design reliability and scalability to future mission needs, and the impact of an orbital environment on the performance of a lasercom system.

Demonstrate Design Liabilities

In addition to the link performance, LCDS will also demonstrate that a lasercom terminal can be designed with system size, weight, and power allocation that are competitive with existing or projected RF technology, while achieving the desired performance objectives. Additionally, the demonstration will show that the cost of developing and fielding the lasercom technology, including the recurring and non-recurring engineering costs, is competitive with potential RF solutions. The design will also minimize technical risk by requiring minimum technology development.

Collect In-Space Performance Data

The demonstration will collect sufficient data over its on-orbit lifetime to confidently validate the communications system performance. This data will be used to support the specification, design, and manufacturing of operational systems. Data obtained should provide for the resolution of any observed anomalies and performance deficiencies during the demonstration and supply the basis for assessing performance and design margins. Performance data collected from the demonstration will be used to validate prediction models for the lasercom link and will permit scaling of the design to different operating regimes.

DEMONS"IRA'I'1ON CONCEPTS

The LCDS demonstration concepts were developed to meet the demonstration objectives, and to provide a low risk demonstration that provides high confidence in achieving the basic goals. In developing each concept, options were examined and compared in a number of areas, including scalability to future applications, technology maturity, cost, and performance. The latter includes the range, geometry, and data rate. Starling with the prime objectives of validating a 750 Mbps link under conditions similar to those identified by the application survey, alternatives concepts were developed and ranked. Two d ifferent concepts were proposed by the two contractor teams. These concepts are summarized in Table 4 and described as follows:

Ball Concept: The Ball team proposed the use of a single spacecraft/lasercom terminal in a geosynchronous transfer orbit (GTO) and companion aircraft/ground terminals to achieve a wide range of demonstrations. With the spacecraft in GTO, link demonstrations can be conducted from LEO to Ground/Air and GEO to Ground/Air. The difference in range permits a single demonstration to validate a wide range of link applications.

Motorola Concept: The Motorola team proposed to develop a space-to-space demonstration in which satellite.s in different orbital planes will establish data communications at an intended rate of 750Mbps (plus necessary data framing overhead). This demonstration concept permits direct validation of link performance under an orbital environment similar to that of LEO-network applications.

TECHNOLOGY READINESS

Lasercom technology, with its significant past investment, is ready for operational use. Assessments of critical technologies for LCDS were conducted during the Mission Definition Study, and concluded that the demonstration can be supported by existing technology with minimum development effort. A number of previous lasercom development programs, most notably

Parameters	Ball concept	Motorola Concept
# spacecraft	1 in GTO	2 in different orbital planes
Orbit	350/35,256 km 28.5 degree inclination 10.5 hr period	'700 km circular Angle between orbital planes =8-32 degrees
Data Rate	1 Gbps LEO-Air, Air-LEO 1 Gbps GEO-Air, Air-GEO 1 Gbps GEO-Ground 10 Mbps Ground-GEO	760.88 Mbps
Range	up 102,500 km for LEO-ground/Air links >30,000 km for GEO-Air/Ground link	1000 -5000km
Space terminal	Volume: 110cm x 57cm x 52cm Mass: < 50kg	Volume: 30cm x 30 cm x 24cm Mass: 12 kg

Table 4. Summary of demonstrat ion cone.cp~

the Laser Communication System (LCS) have led to space qualification of many components and subsystem technologies, including detectors, pointing, acquisition and tracking electronics, gimbals, encoders, motors, mechanisms, optical elements and coating, and communication system high speed electronics. Risk mitigation requirements for these components and subsystems arc minimal.

For communications electronics, the major area of user concern is the laser diode lifetime and high data rate modulation driver. The current concepts of LCDS employ laser diode master oscillator power amplifier (LD-MOPA) with higher power output (0.6-1W average) as the transmit signal source. These devices arc commercially available with a NASA Technology Readiness Level of 5. However, they have not been qualified for space operation, and lifetime and high bandwidth modulation characteristics have not yet been fully demonstrated. Fortunately, suitable alternate exists for the LD-MOPA technology by combining the outputs of several high power laser diodes (SDL 5430s). These diffraction-limited, high power laser diodes have previously been developed to deliver an average power of 150mW with an MTBF in excess of 500,000 hours. Large signal modulation bandwidth in excess of 1GHz has also been demonstrated, Suitable power combining schemes have been demonstrated in previous development programs (FEWS/BSTS). Furthermore, high speed electronics required for driving the laser diodes have also been developed and arc commercially available.

For the spatial acquisition, pointing, and tracking subsystem, the major area of concern is the control system and mechanism needed to achieve fine pointing in the presence of plalform-induced disturbances. High bandwidth beam steering mechanisms have been developed that exhibit control bandwidths in cxccss of 2 kHz. Alternatively, the required control bandwidth can be substantially decreased by employing suitable vibration isolation mechanisms, Both techniques have been validated by ground-based testing, and precision beam pointing and tracking have been demonstrated in space (RME).

CONCLUSIONS

The development of LCDS is directly applicable to future commercial mobile satellite systems that require high bandwidth intersatellite crosslinks. The small size, mass, and power of the lasercom technology makes it ideally suitable for application in satellites constellations with small spacecrafts (e.g. Iridium™ and Teledesic™). In addition to the commercial applications, the development of LCDS is also relevant to NASA's strategic function on space communications by providing a technology capable of improving the data relay services and reducing cost. Furthermore, as a technology with high commercial potential, development of the LCDS can stimulating commercialization so that future NASA and government needs can be met more economically.

Successful completion of the LCDS can validate the technology readiness for the relevant applications, and can lead to fast insertion of the technology into future operations. Furthermore, the flight demonstration can provide. important design and performance data for scaling the technology to other, more ambitious applications.

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[1] Leslie Taylor Associates, Satellite News, May 30, 1994.

[2] FCC Application of Teledesic for Low Earth Orbit Satellite System in the Domestic and International Fixed Satellite Services, March 1994.

[3] FCC Application of Iridium for a Low Earth Orbit Mobile Satellite System, December 1990.